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Structural Analysis Using Applied Element Method: A Review

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ABSTRACT

This paper presents a review on a displacement-based method of structural analysis. In Applied Element Method (AEM), the structure is simulated as an assembly of elements formed by dividing the structure virtually. These elements are connected in both normal and tangential directions by springs. AEM can be used to analyze structural behavior from the initial loading until total collapse. It combines between the advantages of Finite Element Method (FEM) and Discrete Element Method (DEM). In this paper, the differences between AEM and the other numerical methods are discussed. Next, basic introduction to AEM and its assumptions are presented. The element formulation and the effect of number of the connecting springs between elements in addition to the element size are illustrated. Finally, applications of AEM such as cyclic loading condition, dynamic small and large deformation range, creep theory, functionally graded material, masonry building and fiber reinforced polymer and polypropylene composite are explained.

1. Introduction

Numerical methods are widely used in structural analysis. The terms "accuracy", "simplicity" and "applicability "are to be complied within these numerical methods. The term, "accuracy", is supposed to obtain practical results, "Simplicity" means they shouldn't be complex, and "applicability" implements the method in a reasonable CPU time. These three conditions hardly met by a specified numerical technique when current techniques are evaluated [1].

Numerical methods for structural analysis can be categorized as Continuum Method and Discrete Element Method [1-4]. Both categories are based on objective material assumptions. Continuum materials are considered in first category. A prominent example of this category is the Finite Element Method (FEM) [1-3]. Through this method, major cracks are defined by joints but this has the disadvantage of the pre-definition of the position and direction of the crack propagation before the analysis is applied [2, 5, 6]. Since the FEM is focused on continuum material calculations, it is complicated to observe structure failure behavior. Therefore, the FEM can only meet the requirements of "accuracy". On the other hand, it is hard to admit that the FEM fulfills "simplicity" as second requirement. Many complications occur when material or geometric highly nonlinearity is applied [1]. The other category uses methods for discrete elements, including the Distinct Element Method (DEM) and Rigid Body and Spring Model (RBSM) [2, 3]. The DEM assumes that the objective material consists of individual elements and can represent a fully discrete material behavior. A new DEM extension, known as the modified DEM or extended DEM (EDEM) is implemented with the introduction of a joint spring or pore spring which reflects the material continuity. This was applied to the overall failure of varied structures and materials. The RBSM is primarily used for limiting structural analysis, while EDEM is used for the simulation and re-contact of structural members with extremely large deformations [2]. Until complete collapse of systems the analysis using RBSM could not be done. In comparison, the EDEM can detect the structural behavior from zero loading until the structure collapses [3]. The main drawback of these rigid element methods is that the results of the simulation mainly depend on the form, dimension and arrangements of the elements [2, 5]. Additionally, in a small deformation range the accuracy of both methods is lower than of the FEM [2, 5, 6, 7, 8]. The discretization of elements in RBSM and EDEM greatly affects the direction of failure and crack. The fracture behavior, in which cracks generate and spread in many directions, such as cyclically loads, is difficult to follow [2]. The EDEM meets the requirements completely of "simplicity" and partly meets the requirements of "applicability", but still concerns about "accuracy" [1].

The fact discussed above enables us to conclude that these available techniques are not appropriate to pursue a

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total structure behavior with accurate precision and acceptable time from zero to collapse [3]. A new displacement method known as the Applied Element Method (AEM) was recently developed [1, 3]. AEM has a remarkable ability to monitor the behavior of the structural collapse during the different stages of the structure. This covers application of load, elastic stage, start-up and propagation of crack, the yielding of reinforcement, non-linear behavior, large displacement, the separation and collision of element and the dissipation of energy throughout collision [4, 9, 10, 11].

When the structure is subjected to typical loads, the continuum mechanisms rules apply and the FEM can describe the behavior. However, in cases of intense loading including earthquakes, blasts and impact, the behavior of the structure is influenced by the separation and collision of its elements. It is achieved by using the DEM to simulate the behavior of the separated elements. While DEM is reflective of the separation and collision, the continuum elements can not be represented. The wide variety of applications of AEM has a great advantage as it can reflect both the continuum and the discrete behavior of structures. It can also simulate the structure behavior before and during collapse [9, 11].

This paper sheds some light on the Applied Element Method as a vital technique of structural analysis. An overview of this technique including its assumptions, element formulation, element size and connecting springs between elements are illustrated. Moreover, some other points will be highlighted, as cyclic loading condition, dynamic small and large deformation range, creep theory and functionally graded material.

2. Factors affecting structural analysis

The results of the performed analysis in various fields of application should be checked wherever possible by comparing with theoretical or experimental outcomes. The principal factors affecting structural analysis can be described as:

1. Inertia force effects: Load types are classified into static and dynamic conditions of loading. The inertia and damping forces should be considered, as well. Loading is found to be a function of time.
2. Load direction effects: Analyses are classified into two groups, monotonic and cyclic conditions of loading. The load path in monotonic state of loading is unchanged as its value increases. While in cyclic loading, the load path and value are changed.
3. Geometric change effects: Structural dimensional deformations are considered to be small. The structural geometries can be assumed to be constant and the effects of geometric changes are negligible in the stiffness matrix or in internal forces. Deformations are high, and geometrical nonlinear behavior should also be mentioned in other cases, such as buckling.
4. Material characteristics effects: Material behavior can be presumed to be linear or nonlinear. Stress-strain relationships are constant in linear behavior while cracking, yield of the material and nonlinear stress-strain relationships should be considered in nonlinear case [1].

3. Applied Element Method (AEM)

The structure is divided and modeled as an assembly of relatively small elements in the Applied Element Method (AEM) [4, 5 , 12], which was developed in 1996 by Tag-Din and Meguro .The elements are then linked together via a series of normal and shear springs reflecting each element's stress, strain or failure [4, 12]. AEM is capable of modeling the separation, contact and collision of failed elements as well as structure and highly non-linear behavior between external body such as cracking. In the simulation of cracks, crack may propagate in any direction at element boundaries without the need to predefine the position of joint elements such as in FEM. Every reinforcement bar can be taken into consideration with all reinforcement data, like the diameter and location of stirrups and concrete covering. By following each item motion until the structure collapses completely, the zone of failure can be defined around the structure. AEM can thus be effectively carried out with seismic modeling, progressive failure analysis, failure modal evaluation and performance-based structural design. The main advantages of AEM are flexibility, high accuracy, ability to analyze statically and dynamically in small and large ranges of deformation, prediction of structural behavior before complete collapse of structures and a fair processing time [12].

When using AEM in linear static analysis, the following assumptions are considered [4]:

- Elements are supposed to be rigid (this means that the applied load does not alter their shape and size).
- Elements are assumed to be linked with number of springs.
- Assembly of rigid mass and springs acts as a rigid body spring mass model.
- The deformations of an element are supposed to be similar to spring deformation.
- Loading path for problem analysis is considered to be constant

4. AEM modeling

4.1. Element formulation

In AEM, the structure is divided into small rigid elements. The elements can be in various shapes depending on the structural geometry. Fig. 1 shows two elements supposed to be bound to a single contact point via normal and shear springs. The elements can be considered in either a 2-D analysis with three degrees of freedom, or in 3-D analysis with six degrees of freedom, as shown in Fig. 2. These degrees of freedom actually demonstrate the elements rotations and translations. A unit displacement at the centroid of the element is applied to determine the element stiffness matrix of any pair of springs around the element, and the forces at the other degrees of freedom are calculated if they are fixed [12,13]. This results in a small, only sized stiffness matrix (6*6). For an arbitrary contact point, as indicated in Fig .1, the stiffness matrix is derived with a pair of normal and shear springs. The total stiffness matrix is calculated by adding the stiffness matrices of each spring around each element. Therefore, the generated stiffness matrix is the average stiffness matrix for the element. Spring failure is based upon the assumption of zero stiffness. The upper-left quarter of the stiffness matrix is indicated in Equation (1). This formula is based on the point of contact (distance L and the angles ө and α) of the element stiffness matrix and the stiffness of normal and shear springs that are calculated in the contact point position based on stress and strain [5]. There is no need to describe shape functions and no integration processes for calculating stiffness matrix in AEM and this makes it faster than FEM [12].

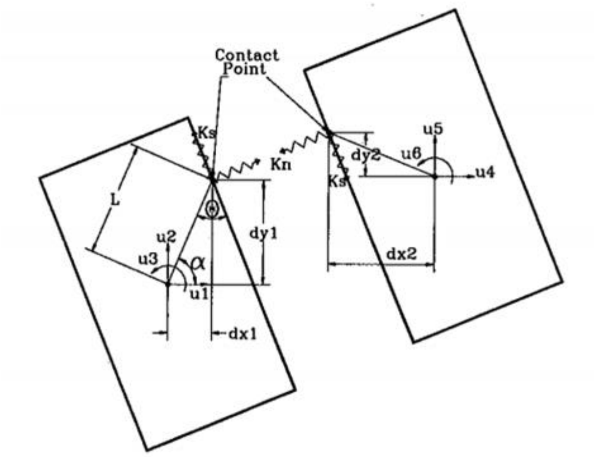


Fig. 1. Element shape, contact point and degrees of freedom for two elements [5]

4.2. Connectivity between elements

Generally, FEM is based on structural elements modeling such as frame elements or shell elements. Adjacent elements are connected by their common nodes, so that partial connectivity is not permitted and element failure and separation can not be modeled [9]. Though object modeling in AEM is very familiar to FEM, the key difference between AEM and FEM is how the elements are combined. The separation of elements can simply be simulated in AEM compared to FEM because of the use of springs between the element surfaces. For certain cases, the size of elements in the structure is modified and a transition zone is needed for transmitting large elements from small elements in FEM while the region is not necessary in AEM. This leads to a significant reduction in the number of elements (Fig. 3). Besides, AEM used a connectivity between these two elements by mans of springs only in part of the surface not in the total surface, but the connectivity can not be modelled in FEM without alternative mesh techniques [9, 12], as can be seen in (Fig. 4).

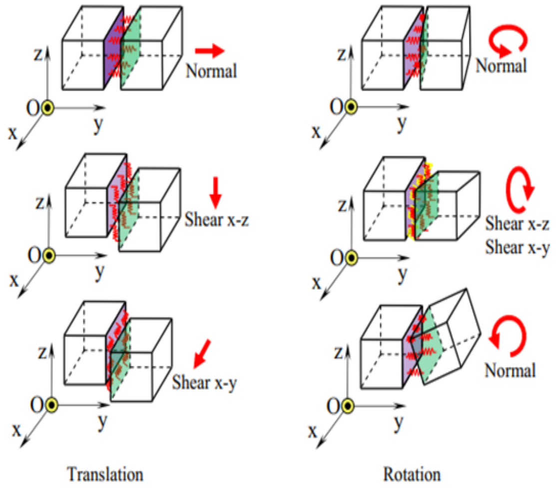
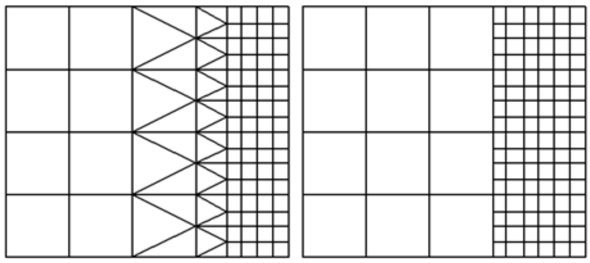
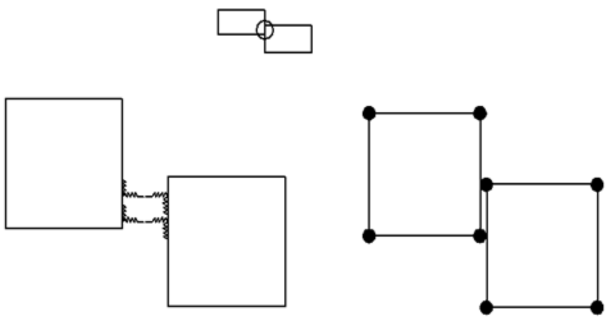


Fig. 2. Six degrees of freedom in 3-D analysis and connecting springs [11]



(a) (b)

Fig. 3. Transition from Large Elements to Small Elements in: (a) FEM, (b) AEM[12]

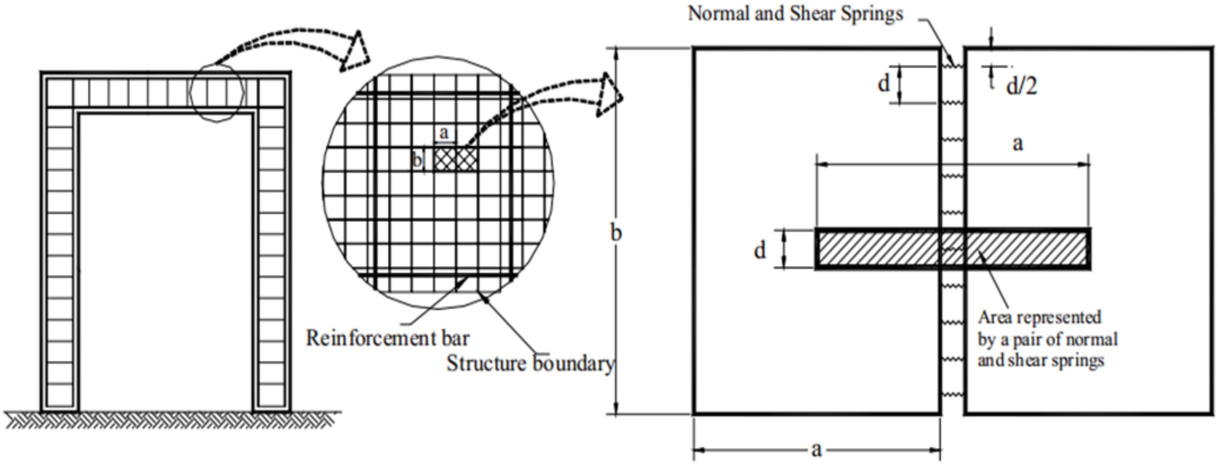


(a) (b)

Fig. 4. Element Connectivity; (a) AEM (connectivity via springs), (b) FEM (no connectivity) [12]

4.3. Spring stiffness determination

In AEM analysis, each normal and shear spring stiffness is expected to reflect a certain area of the connected blocks. The position of the spring around one element edge is shown in Fig .5. Stiffness of the spring is determined by Equation (2) where, "d" is a distance between the springs, "T" is the element thickness and "a" is the representative area. "E" and "G" are the Young and shear modulus of concrete respectively. For springs in steel, the term (d*T) will transfer to the steel bar area while E and G are the Young and shear modulus of steel [5, 11].



(a) (b)

Fig. 5. Modelling of structure in AEM: (a) Element generation for AEM, (b) Spring distributions and area of influence of each spring [10]

When the stiffness matrix is defined, displacements are determined by Equation (3) where, "K" is a global stiffness matrix, Δ is displacement vector and "F" is load vector calculated by translating applied loads to nodal forces in the element centroid. Spring deformations and forces, stresses and strains around any element are estimated by using the computed displacements [11, 12].

4.4. Constitutive model and failure model

The constitutive model of the materials should be specified. For example, the concrete is modeled with the constitutive model shown in Fig. 6. The compression envelope is defined by three parameters—the initial Young's modulus, the fracture parameter that reflects the internal damage of the concrete, and the compressive plastic strain. The stress-strain response of concrete springs is believed to be linear before they reach the cracking point. The stiffness under stress is set to be null after cracking. the previous steel spring loading history. Separation strain may be used to characterize total concrete or steel failure. The spring matrix of the element shall be considered to be removed from the element if the strain on an element which represents a concrete or steel exceeds the separation strain, to separate the element from neighboring elements. For reinforcement, the steel bars will be deemed cut if the steel stress reaches the ultimate stress, or if the concrete covering the bars reaches separation strain. The separation strain of concrete thus influences the failure of reinforced concrete structures. By adjusting the separation strain, the ductility or brittleness of the structure can be controlled [14].

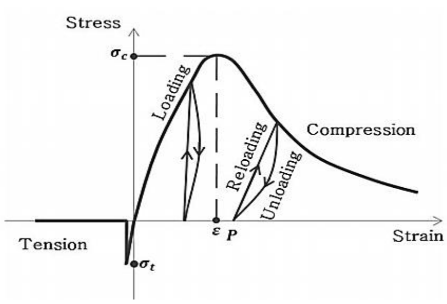


Fig. 6. Axial stress-strain curves for concrete [14]

$$\begin{vmatrix} k_n\sin^2(\theta+\alpha) + k_s\cos^2(\theta+\alpha) & -k_n\sin(\theta+\alpha)\cos(\theta+\alpha) + k_s\sin(\theta+\alpha)\cos(\theta+\alpha) & k_sL\sin(\alpha)\cos(\theta+\alpha) - k_nL\cos(\alpha)\sin(\theta+\alpha) \\ -k_n\sin(\theta+\alpha)\cos(\theta+\alpha) + k_s\sin(\theta+\alpha)\cos(\theta+\alpha) & k_s\sin^2(\theta+\alpha) + k_n\cos^2(\theta+\alpha) & k_nL\cos(\alpha)\cos(\theta+\alpha) + k_sL\sin(\alpha)\sin(\theta+\alpha) \\ k_sL\sin(\alpha)\cos(\theta+\alpha) - k_nL\cos(\alpha)\sin(\theta+\alpha) & k_nL\cos(\alpha)\cos(\theta+\alpha) + k_sL\sin(\alpha)\sin(\theta+\alpha) & k_nL^2\cos^2(\alpha) + k_sL^2\sin^2(\alpha) \end{vmatrix} \quad (1)$$

$$k_n = \frac{E*d*T}{a} \text{ and } k_S = \frac{G*d*T}{a} \quad (2)$$

$$F = K\Delta \quad (3)$$

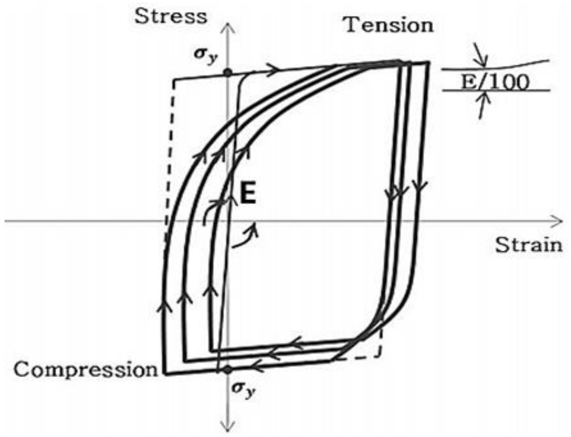


Fig. 7. Axial stress-strain curves for steel [14].

5. Mesh sensitivity effects

This section displays the effect of different dimension, and arrangement of elements in addition to number of connecting springs between elements and the element size on the analysis results in AEM.

5.1. Effect of number of connecting springs between elements

A significant factor to consider is the number of connecting springs between elements. Clearly, the increase in connecting springs between elements in nonlinear analysis helps to obtain better results of crack propagation. Even in elastic analysis, the number of connecting springs was found a significant parameter. Referring to Fig .5(b), the width of the spring is "d". The number of connecting springs does not affect the stiffness of the element for translation degrees of freedom since a decrease in the number of connecting springs results in an increase of the area covered by each pair of springs. Eventually, the total area is the same as a whole item. Shear springs with normal springs are mainly resistance to rotation of an element. Theoretically rotational stiffness K_r from normal springs is determined by

$$K_r = \int_{y=-b/2}^{y=b/2} \frac{ET}{b} z^2.dz = \frac{ETb^2}{12} \qquad (4)$$

Where, T is element thickness and E is Young’s modulus. The rotational stiffness of element is accomplished by combining all the separately determined rotational stiffness for each spring. The total rotational stiffness can be easily demonstrated

$$K_r = \frac{ETb^2}{4n^3} \sum_{i=1}^{n} (i-0.5)^2 \qquad (5)$$

Where, i spring number and 2n number of springs. Table 1 indicates the relation between the number of springs and the percentage of error between the theoretical and calculated results.

Table 1. Relation between Number of Connecting Springs and Calculated Error [3].

2n	2	4	6	8	10	20
Error Ratio % $([(K_r{}^n/K_r{}^t)-1)*100]$	25	6.3	2.8	1.6	1.0	0.3

For two connecting springs, value of rotational stiffness obtained is smaller by 25 percent than the theoretical value, which is very high. Moreover, if the number of springs is 10 or more, the error decreases to 1 percent. This effect is dominant if the element size compared to the structure size is relatively large. If the element size is small, the error vanishes [2, 3].

5.2. Effect of element size

It’s really important to change element size in the analysis. Modeling of structures with large-size elements increases structure stiffness and structure failure load. The calculated displacements are thus decreased and the failure load is greater than actual one. A series of simulations was conducted using laterally loaded cantilever models as shown in Fig .8. The experiments were conducted using two models of ten and twenty springs that connect each pair of adjacent element faces for each case for various element size to discuss the effect of the number of connecting springs. It is obvious from the figure that increasing the number of base elements allows the error to be reduced, thus raises the CPU time. A single element on the base is a theoretically calculated displacement error of approximately 30 percent. When the number of elements in the base increased to 5 or more, this error decreased to less than 1 percent. Yet the time of the CPU is quickly increased. Although the time of the CPU for 10 springs is approximately half the time for 20, the accuracy of 10 springs modeling is similar to the accuracy of 20 springs. It can be inferred from this figure that the use of large numbers of elements together with relatively few springs contributes to a high degree of accuracy during CPU time. In order to enhance the accuracy of the elastic analysis, the number of elements rather than the number of connecting springs should be increased.

The distribution of normal and shear stresses for different number of base elements at the base columns examined is shown in Figs. 9 and 10. The following should be noted from these figures:

- Calculated normal stress, even with the reduced number of elements at the base, are very similar to the theoretical values.
- The shear stress values for the same element are unchanged.
- In the case of a smaller number of elements, the shear stress values are far from theoretical values and become similar to the theoretical results as the number of elements increases.

This means that elements of relatively large size can simulate the behavior in which the effect of shear stresses is minimal, such as for slender frames. The unsupported length of the structure should be taken into account in order to maximize the accuracy of the study of large elements. Elements of small size can be used in deep beams and walls to track fracture behavior in the dominant shear zones

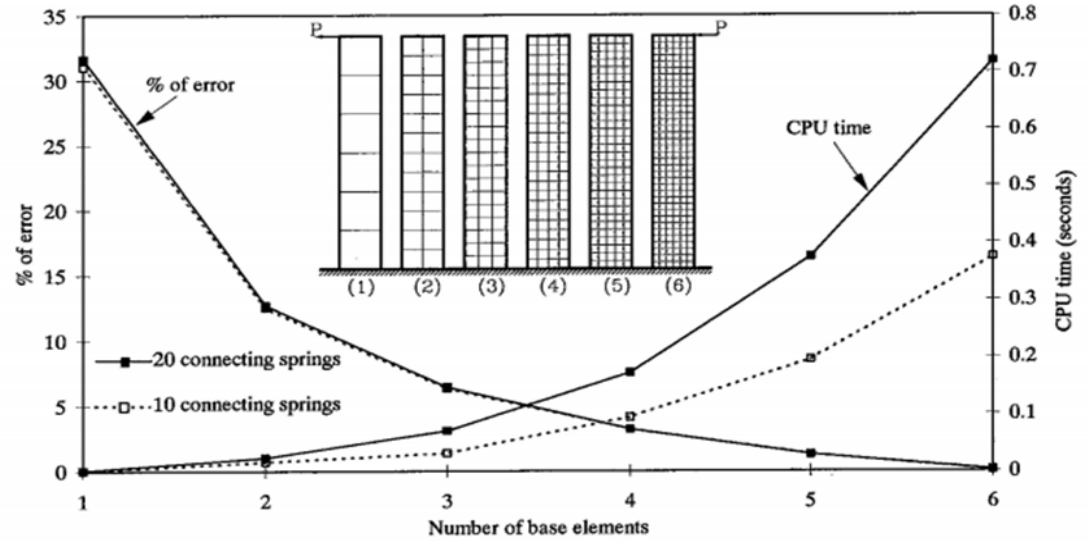


Fig. 8. Relations between number of base elements,ratio of error and CPU time[2, 3]

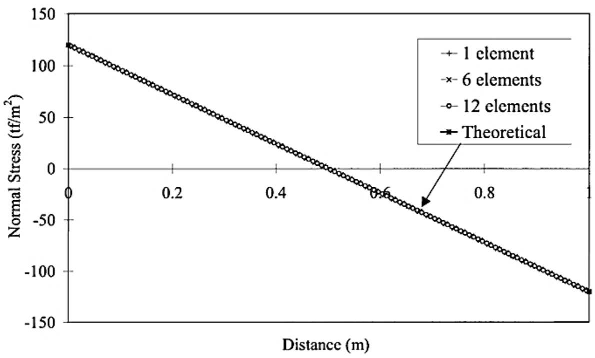


Fig.9. Normal stress distribution at column base[1, 2].

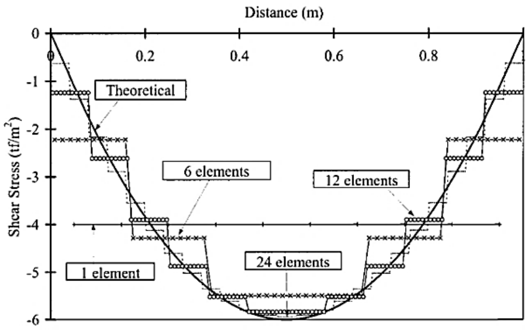


Fig.10. Shear stress distribution at column base[1, 2]

[2, 3].

A code of MATLAB was created to get deflection, reactions and bending moment of plain concrete beam shown in Fig. 11. The results are shown in Fig .12. The calculated deflection is at 400 mm away from point load. Fig .12 shows the deflection was improved with an increase in the number of elements for a particular number of springs.

As the number of springs increases, the calculated deflection converges. No change in the outcomes is achieved beyond 5 springs. Therefore, the number of elements should be increased rather than increasing the number of springs. The reactions are precisely calculated even with less elements and springs [13].

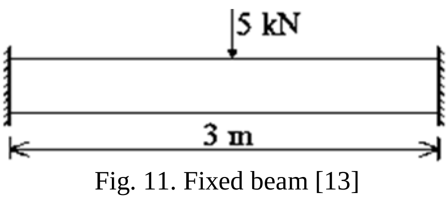


Fig. 11. Fixed beam [13]

6. Structure damage

Buildings are affected by various types of damage. The structure damage can be categorized in 7 groups as listed in Table 2, according to the Architecture Institute of Japan. The structural and non-structural elements without the collapse of structure are partially damaged in the first five groups. Partial and full total collapse of structures is an important topic in research because it causes significant causalities with and outside of the structure. Therefore, the failure of a structure may lead to neighbor structures failure or collapse [1].

7. AEM versus other numerical methods

Although the FEM remains robust and stable, its capability to simulate progressive collapse is doubtful [15]. The progressive collapse term is used to demonstrate the spread of local failure as a chain reaction that results in the building's partial or total collapse. Progressive collapse key feature is that the total damage is out of proportion with the actual cause [11, 14]. Several factors, including design and construction errors and loading events beyond the usual structure design bases, can cause a progressive collapse that is rarely regarded by the structural engineer. As the building is damaged, progressive collapse will lead to huge death and property damage [16]. There is a limited and very time-consuming possibility to fully separate the elements. The AEM is, on the other hand, able to model the progressive collapse of structure effectively [14, 15].

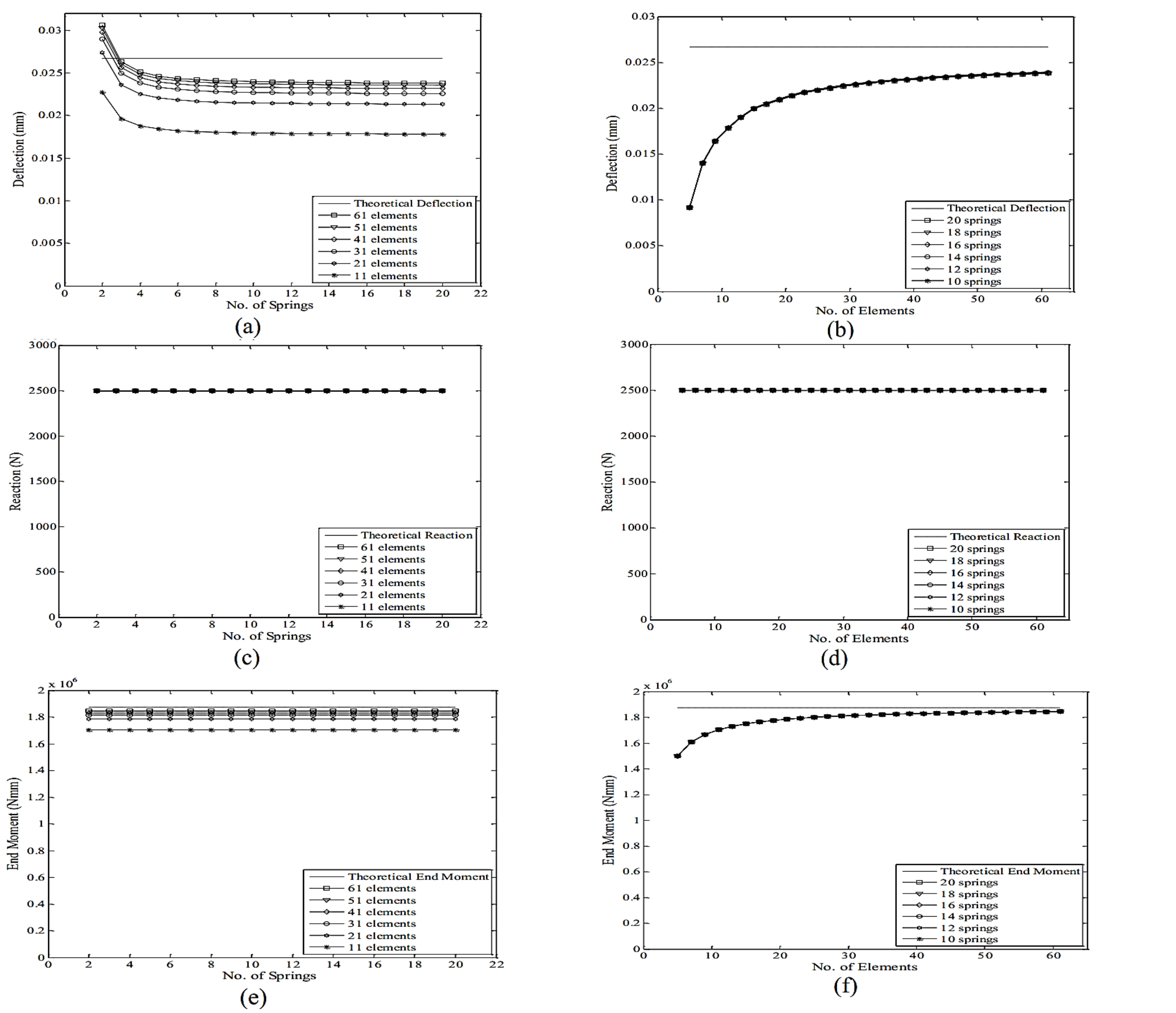


Fig.12. Results (a) deflectin vs number of spings, (b) deflection vs number of elements, (c) reactions vs number of spings, (d) reactions vs number of elements, (e) end moment vs number of spings, (f) end moment vs number of elements [13].

Table 2. Structures damage level by AIJ [9]

Damage level	Damage of members
1- No damage	No damage is found.
2-Slight damage	Columns, shear walls or non-structural walls are slightly damaged.
3-Light damage	Columns or shear walls are slightly damaged. Some shear cracks in non- structural walls are found.
4-Moderate damage	Typical shear and flexural cracks in columns, shear cracks in shear walls, or severe damage in non-structural walls are found.
5-Heavy damage	Spalling of concrete, buckling of reinforcement, and crushing or shear failure in columns are found. Lateral resistance of shear walls is reduced due to heavy shear cracks.
6- Partial collapse	A building is partially collapsed due to severely damaged columns and/or shear walls.
7- Total collapse	The building is totally collapsed due to severely damaged columns and/or shear walls.

A successful method to simulate many granular flow situations was demonstrated by the DEM. Within the DEM it is presumed that the material consists of separate, discrete particles that can have various forms and characteristics. The simulation begins when all particles are placed in a certain location and an initial speed is given to them. The forces acting on each particle are then determined by the relevant physical laws. A method of integration is used to calculate change in position and speed of each particle within a certain period of time from the laws of Newton. The new positions are then used in the next step to calculate forces and this loop is repeated until the simulation is complete. DEM is not a stiffness-based method, unlike AEM. The solution relies upon the transfer of force from one particle to another, so the DEM is not a practical solution to large-scale problems. Another challenge in the DEM is that simulations are typically limited to spherical particles because calculation cost is increased with increasing geometry complexity [15]. A comparison between for AEM, FEM and DEM is shown schematically in Fig .13.

8. Areas of AEM application

In contrast with other methods, the geometrical stiffness matrix is not necessary in the AEM. This generalizes the method and applies to several types of loading [6].

8.1. Cyclic loading analysis

In cyclic load analysis, one of the key issues is how the crack closure process is treated. This problem is slight because the cracks mainly opened after cracking in the monotonic loading state. But some cracks are closed in cyclic loading after the reversal of the load direction and new cracks are formed. Cracks are expressed by separation between elements in the methods using discrete elements. While the analysis is more practical, there are various complexities. The separation of elements on both sides causes these complexities. The displacement of this element has no numerical connection to the displacement of the surrounding element when the springs around the element are cut off. If the crack still open, for example when the load is monotonic, this problem has no significant implications.

The accuracy of the AEM is confirmed in the study of cyclic loading in static condition. Initiation and propagation of crack problems were studied. It should be pointed out that while the element shape used in the simulation is square. The generation or propagation of cracks in the material is not affected. Slender structures under cyclic loading are expected to have a high accuracy when the bending failure occurs [2].

8.2. Large displacement range

While a geometrical stiffness matrix is taken into account in the FEM as an effect of large displacements, no such matrix is required in the AEM. One limitation of AEM is the assumption of constant direction of the applied forces. As a consequence of this, the AEM can not evaluate loading condition in which the direction of force changes if a member buckles. For static large deformation analysis, the following modification is presented.

$$K\Delta U = \Delta f + R_m + R_G \quad (6)$$

where K is the nonlinear stiffness matrix, ΔU and Δf the incremental displacement and force vector, R_m the residual force vector for cracking and incompatibility between strain and stress of the spring, and R_G the residual force vector for geometric structural modification while loading.

When the geometrical residues are taken into account, the load displacement relationship is close to theoretical values even when the displacement is very large. This demonstrates that the AEM is accurate and numerically stable. The AEM has the strength to monitor the behavior of any point in the structure accurately, even when there is a large deformation. Its accuracy of AEM is verified through the comparison of numerical results for buckling and post buckling with theoretical results; agreement is excellent [6].

8.3. Dynamic small and large deformation range

In a small deformation range, the general dynamic equation of motion is:

$$[M][\Delta\ddot{U}] + [C][\Delta\dot{U}] + [K][\Delta U] = \Delta f(t) - [M][\Delta\ddot{U}_G] \quad (7)$$

where [M] is mass matrix, [C] damping matrix, [K] nonlinear stiffness matrix, Δf(t) incremental load vector, [ΔU] incremental displacement vector, $[\Delta\dot{U}]$ incremental velocity vector, $[\Delta\ddot{U}]$ incremental acceleration vector and $[\Delta\ddot{U}_G]$ gravity acceleration.

For rigid body motion analysis, the mass matrix is very important. After failure due to cracking or element separation, the stiffness matrix becomes singular. It implies that the determinant of the matrix slowly decreases until it is zero. A stiffness matrix with little value of determinant is usually incorrect. This implies that outcomes acquired just before the structure collapse or partially collapses are not reliable. This problem does not arise if the analysis is done in a dynamic case, since even after the failure; a mass matrix is inserted into the stiffness matrix.

In a large deformation range, the general dynamic equation of motion is:

$$[M][\Delta\ddot{U}] + [C][\Delta\dot{U}] + [K][\Delta U] = \Delta f(t) + R_m + R_G \quad (8)$$

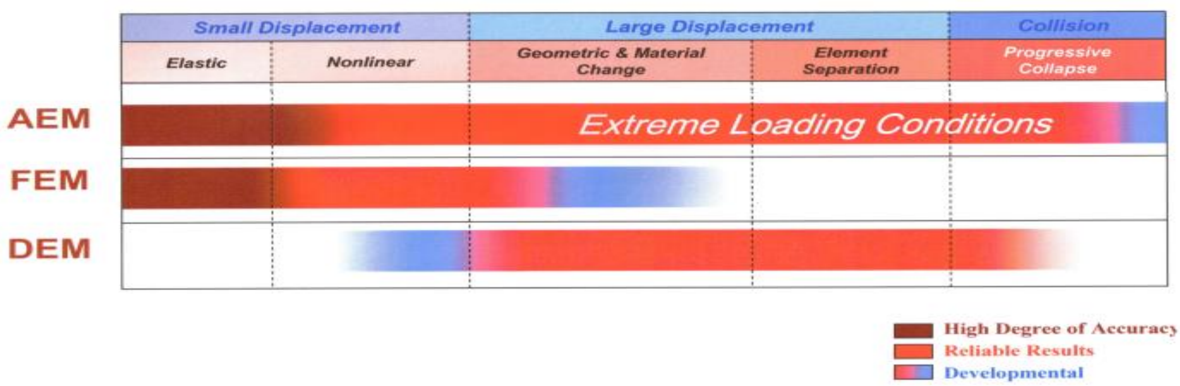


Fig. 13. A comparison between AEM, FEM and DEM [9]

where R_m represents additional load vectors because of the material nonlinear behavior. The structure geometry is modified after adding a small load increment, and thus incompatibility is achieved between external load and other forces. The additional load vector R_G is generated. Dynamic load analysis structures allow us to observe both geometric structural changes and rigid body motion during failure. As a small increment in load, a little time increment is required to be used with each load increment [8].

8.4. Creep theory

The AEM can be applied in creep theory problems. Transverse deformations are not taken into account in the formula. The effect of the Poisson's ratio can be disregarded in problems such like beams and frames bending. If the body surface defines only the static boundary conditions, the distribution of stress does not depend on the Poisson's ratio. In certain cases, the Poisson's ratio will greatly impact the stress-strain state [17]. There is a way of taking the Poisson ration into account, which consists in modifying the stiffness matrix [3].

8.5. Functionally graded material

A substitute for laminated composite materials is functionally graded material (FGM). In FGM, the properties change continuously across the depth in contrast to the laminated composite material. It is used extensively in aerospace, biomechanics, automobile, etc. Static and dynamic analysis of FGM is therefore of today's concern. The stiffness matrix and mass matrix are developed and the process for calculating stress and strain is discussed at different points in FG beams. The deflection and stress distribution calculated accurately from AEM are compared with empirical method. The natural frequency of beams with various ratios of length to depth and support conditions is calculated and compared. The AEM can easily be used for FGM [18].

8.6. Masonry buildings

Masonry building failure is considered as the main cause of the huge number of deaths in recent earthquakes worldwide. AEM is tried to study masonry structures with detailed failure involving the occurrence of the cracks, their progress, separations of block and material loss before collapse. The springs have the characteristics of the domain material in the respective area (Fig .14). Since AEM has so far been used for homogeneous media such as concrete and soil, it needs to establish a technique that can address particular features of masonry for the production of heterogeneous, multi-phase material such as masonry. the development of certain strategies for the development of applications for heterogeneous blocky material. Within the framework of AEM, masonry modeling can be carried out easily. Through comparing experimental observation with empirical results, the applicability of the AEM was confirmed .

For the experimental wall, simulation of wall behavior using AEM was made to compare between experimental observation and numerical outcomes. The study for walls of practical dimension was extended to estimate the behavior under various construction and loading variables as a strong agreement between experimental results and numerical prediction was observed. Clay brick masonry wall with central opening test is selected for study. It is roughly square with a single brick 200 X 100 X 50 mm with a mortar thickness of 10 mm. The wall and boundary condition is shown in fig. 15. Crack pattern observed in test and obtained through analysis are shown fig. 16, and Load-displacement curve is shown in fig. 17[19].

8.7. Fiber reinforced polymer and polypropylene composite

The strong material fiber reinforced polymer (FRP) increases the shear strength significantly. Not only does polypropylene band keep the masonry wall structure in one unit but also provides a high capacity for deformation at very low retrofitting costs. A FRP and PP-band composite is applied on masonry wall surface. A combination of these two materials not only can improve the shear and bending, but also the capacity of the masonry structures to deform and dissipate energy. In order to study the masonry structures retrofitted by composite materials, the current AEM is updated. The updated AEM is a good numerical method for carefully estimating retrofitted and non-retrofitted masonry wallets for peak load and failure sequence [20].

Progressive collapse of post-tensioned RC flat slab

8.8. Progressive collapse of post-tensioned RC flat slab

Post tension slabs with a relatively small slab thickness are primarily designed to cover wide spans. The AEM was used in the evaluation of progressive collapse resistance of RC post-tensioned flat slab structure. A post-tensioned RC flat slab structure consists of typical 10 stories with a surface area of 2500 m2 adopted. All floors have a clear height of

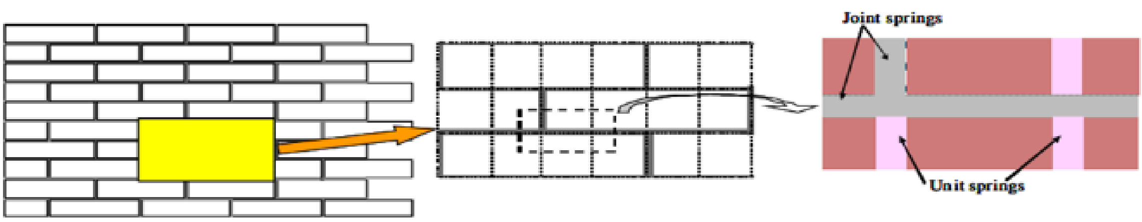


Fig. 14. Masonry discretization[18].

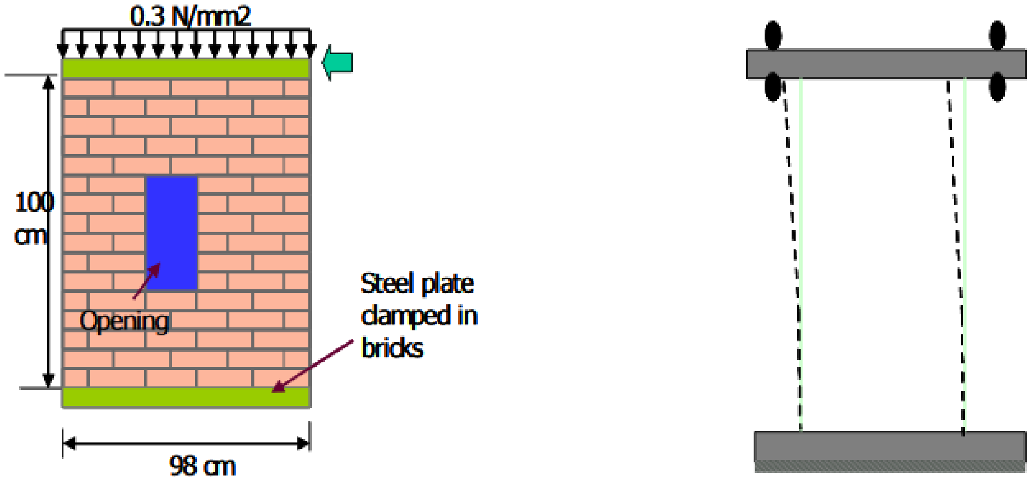
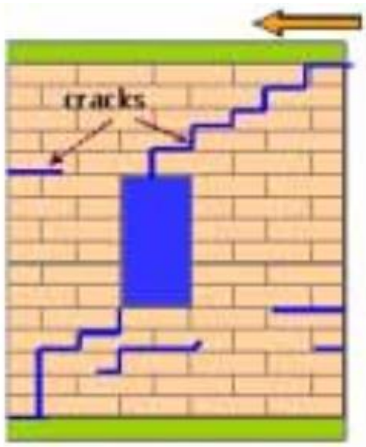
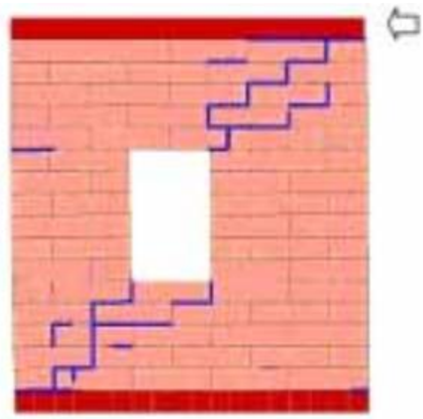


Fig. 15. Test wall and schematic boundary condition[19].



Experimental crack pattern



Observed crack pattern from numerical simulation

Fig. 16. Crack pattern observed in test and obtained through analysis[19].

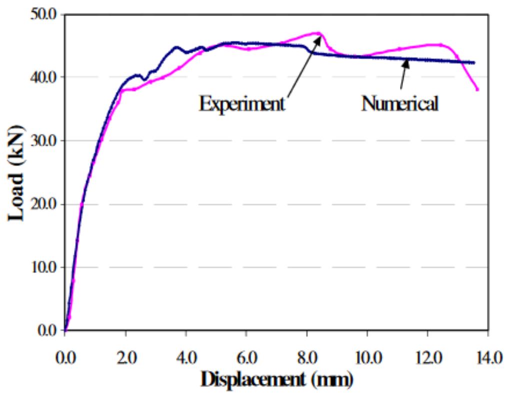


Fig. 17. Comparison of experimental and numerical analysis results[19].

3m. The thickness of the slab used is 280 mm, with tendons spaced 1.25 meters in both directions, spread around the slab. The structure is supported as shown in fig. 18 . Using Extreme Loading for Structures (ELS) software, a 3D model was applied model all structural details and the post-tensioned tendons.

Analytical cases for a typical multistory structure would be as follows:

- Removal of Corner Column.
- Removal of edge column.
- Removal of internal columns.
- Removal of Edge Shear Wall.
- Removal of the internal shear wall.

After the removal of the various vertical supports, distinct structural behaviors were observed. Some cases showed

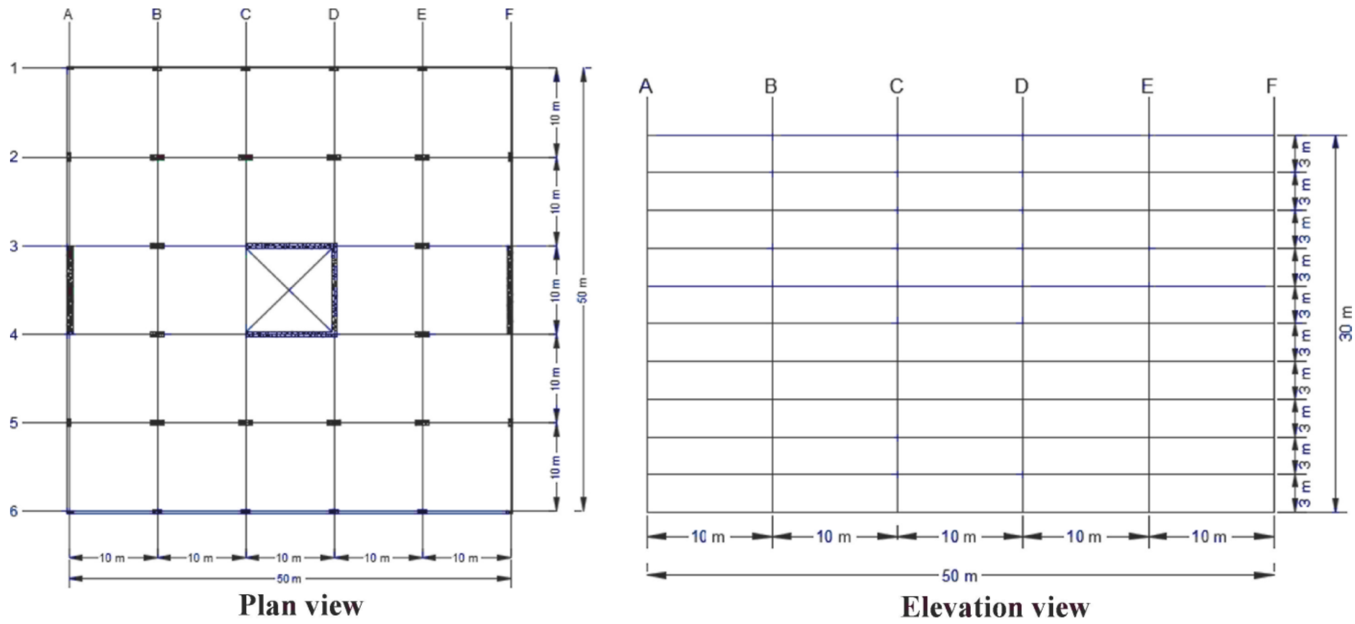


Fig. 18. General Structure Dimensions and supports[21].

resistance to elimination of vertical support and other cases have shown partial collapse[21].

9. Conclusion

Applied Element Method is simple, accurate and suitable for wide range of problems. AEM has thefollowing advantages:

- Displacement can be accurately calculated when the size of element is small.
- Less element size with fewer connecting springs gives accurate outcomes
- In shear dominant cases elements of small size should be used to obtain accurate shear stresses.
- If the element size is relatively high , the number of connecting springs should be high.
- Formulation of element is clear.
- Compared with FEM, modeling time is very short
- Before the analysis, no prior knowledge about location and direction of crack propagation is needed.
- While the element form is square, in a monotonic loading case it has little to no effect on the propagation direction of crack.
- During the collapse the rigid body motion and collision of structural elements can be monitored accurately.
- AEM is valid in a wide range. This can be used for static and dynamic cases, monotonic and cyclic. It can be used for small and large defamation.
- AEM is a good method to efficiently evaluate the behavior of creep, nonlinear material such as masonry, and functionally graded material

References

[1] K. Meguro, Applied element method: a new efficient tool for design of structure considering its failure behavior, Institution of Industrial Science (IIS), the university of Tokyo, Japan, September, pp. 1-20, 2001.

[2] H. Tagel-Din and K. Meguro, Applied Element Simulation of RC Structures under Cyclic Loading. Journal of Structural Engineering, Japan Vol. 127, No. 11, pp.1295-1305,2001.

[3] K. Meguro and H. Tagel-Din, Applied Element Method for Structural Analysis: Theory and Application for Linear Materials. Structural Eng. /Earthquake Eng. Vol. 17, No. 1, pp. 31-45, 2000.

[4] V. Gohel, P.V. Patel and D. Joshi,Analysis of Frame using Applied Element Method (AEM). Procedia Engineering Vol. 51, pp.176–183, 2013.

[5] K. Meguro and H. Tagel-Din, A new efficient technique for fracture analysis of structures. Bulletin of Earthquake Resistant Structure Research Center, IIS, University of Tokyo Vol. 30, pp.103-116, 1997.

[6] H. Tagel-Din and K. Meguro, Applied Element Method used for large displacement structure analysis. Journal of Natural Disaster Science, Japan Vol. 24, No. 1, pp.25-34, 2002.

[7] H. Tagel-Din and K. Meguro, Analysis of a small scale RC building subjected to shaking table tests using applied element method. 12th World Conference on Earthquake Engineering. New Zealand, pp.1-8, 1999.

[8] H. Tagel-Din and K. Meguro, Applied Element Method for dynamic large deformation analysis of structures. Structural Eng. /Earthquake Eng., JSCE Vol. 17, No. 2, pp. 215–224, 2000.

[9] Y.M. Tokal-Ahmed., Response of bridge structures subjected to blast loads and protection techniques to mitigate the effect of blast hazards on bridges (Doctoral dissertation, Ph. D. Thesis, Graduate School New Brunswick, New Brunswick, New Jersey), 2009.

[10] H. Wibowo, S. Reshotkina and D. Lau, Modelling progressive collapse of RC bridges during earthquakes. CSCE Annual General Conference, pp. 1–11, 2009.

[11] M. Lupoae and C. Bucur, Building Demolition – Positive Aspect of Progressive Collapse. MTA Review, XIX Vol. 4, pp. 399-408, 1999.

[12] A. Shakeri, K. Bargi ,Use of applied element method for structural analysis. KSCE J. Civ. Eng. Vol. 19, No. 5, pp. 1375–1384, 2015.

[13] D.L. Christy, T.M.M. Pillai and P. Nagarajan, Analysis of concrete beams using applied element method, IOP Conference Series: Materials Science and Engineering Vol. 330, No. 1, p. 012117, 2018.

[14] H.S. Kim, H.H. Wee, Separation strain for progressive collapse analysis of reinforced concrete building using applied element method. Advances in Structural Engineering Vol. 19, No. 3, pp. 437–448,2016.

[15] D. Asprone, A. Nanni, H. Salem and H. Tagel-Din, Applied Element Method Analysis of Porous GFRP Barrier Subjected to Blast. Advances in Structural Engineering Vol. 13, No. 1, pp. 153–169, 2010.

[16] B.R. Ellingwood, Mitigating Risk from Abnormal Loads and Progressive Collapse. Journal of Performance of Constructed Facilities Vol. 20, No. 4, pp. 315–323, 2006.

[17] A.S. Chepurnenko, A.A. Savchenko and V.S. Chepurnenko, Applied element method in the solution of plane problems in the theory of creep. Materials Physics and Mechanics Vol. 42, No. 4, pp. 455-460, 2019.

[18] D.L. Christy, P. Nagarajan, and T.M.M. Pillai, Development of Elements for Analysis of Functionally Graded Beams Using Applied Element Method. Arabian Journal for Science and Engineering Vol. 45, pp. 4053-4065, 2020, doi:10.1007/s13369-020-04375-z.

[19] B.H. Pandey and K. Meguro , Simulation of Brick masonry wall behavior under in plane lateral loading using applied element method. In 13th World conference on earthquake engineering, Vancouver, BC, Canada Vol.16,2004.

[20] S.M. Umair, M. Numada and K.Meguro, Applied Element Method Simulation of Fiber Reinforced Polymer and Polypropylene Composite Retrofitted Masonry Walls. Advances in Structural Engineering Vol. 17, No. 11, pp. 1567–1583, 2014.

[21] A. Mahrous, M. Ehab, H. Salem, Progressive Collapse Assessment of Post-tensioned Reinforced Concrete Flat Slab Structures Using AEM, Engineering Failure Analysis, Vol.109, 104278, 2020.